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(71) Applicant:
Sumitomo Electric Industries, Ltd.
Osaka-shi, Osaka 541-0041 (JP)

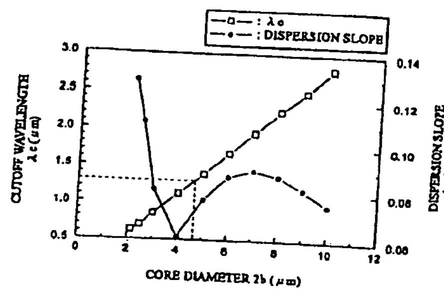
(72) Inventors:
- Kato, Takatoshi
  Sakae-ku, Yokohama-shi Kanagawa 244-8588 (JP)
- Okuno, Toshiaki
  Sakae-ku, Yokohama-shi Kanagawa 244-8588 (JP)
- Sasaoka, Eisuke
  Sakae-ku, Yokohama-shi Kanagawa 244-8588 (JP)

(74) Representative:
Ritter und Edler von Fischern, Bernhard, Dipl.-Ing. et al
Hoffmann Eitle,
Patent- und Rechtsanwälte,
Arabellastrasse 4
81925 München (DE)

(54) **Dispersion-shifted fiber**

(57) The present invention provides a dispersion-shifted fiber which can effectively restrain nonlinear optical effects from occurring and is suitable for long-haul transmission. As characteristics at a wavelength of 1,550 nm, this dispersion-shifted fiber has a dispersion whose absolute value is from 1.0 to 4.5 ps/nm/km, an effective core cross-sectional area of at least 70 μm^2, a cutoff wavelength of at least 1,300 nm at a fiber length of 2 m, and a dispersion slope of 0.05 to 0.09 $ps/nm^2/km$. Also, in this dispersion-shifted fiber, the position where the optical power distribution in the fundamental mode of the signal light is maximized is radially separated from the center of the core region by a predetermined distance, and, when the optical power in the fundamental mode of signal light at the center of core region is P_0 and the maximum value of the optical power distribution in the fundamental mode is P_1, the maximum value P_1 is greater than the value of 1.2 times the optical power P_0 at the center of core region.

Fig.3



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Description

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a single-mode optical fiber applied to a transmission line for optical communications or the like and, in particular, to a dispersion-shifted fiber suitable for wavelength division multiplexing (WDM) transmission.

Related Background Art

Conventionally, in optical communication systems employing single-mode optical fibers as their transmission lines, light in the wavelength band of 1.3 μm or 1.55 μm has often been utilized as signal light for communications. Recently, from the viewpoint of reducing transmission loss in transmission lines, the light in the 1.55-μm wavelength band has been in use more and more. The single-mode optical fiber applied to such a transmission line for light in the wavelength band of 1.55 μm (hereinafter referred to as 1.55-μm single-mode optical fiber) is designed so as to nullify its wavelength dispersion (phenomenon in which pulse wave broadens because the propagating speed of light varies depending on its wavelength) for light in the wavelength band of 1.55 μm (thus yielding a dispersion-shifted fiber having a zero-dispersion wavelength of 1.55 μm). As such a dispersion-shifted fiber, for example, Japanese Patent Publication No. 3-18161 discloses a dispersion-shifted fiber having a refractive index profile of a dual-shape-core structure, whose core region is constituted by an inner core and an outer core having a refractive index lower than that of the inner core. Also, Japanese Patent Application Laid-Open No. 63-43107 and Japanese Patent Application Laid-Open No. 2-141704 disclose a dispersion-shifted fiber having a refractive index profile of a depressed cladding/dual-shape-core structure, whose cladding region is constituted by an inner cladding and an outer cladding having a refractive index greater than that of the inner cladding. Further, V.A. Bhagavatula et al., OFC' 95 Technical Digest, Paper ThH1, 1995, and P. Nouchi et al., ECOC' 96, Paper MoB.3.2, 1996 disclose a dispersion-shifted fiber having a refractive index profile of a ring-shaped core structure.

Recently, on the other hand, since long-haul transmission has become possible with the advent of wavelength division multiplexing (WDM) transmission and optical amplifiers, there have been proposed, in order to avoid nonlinear optical effects, dispersion-shifted fibers employing a refractive index profile of the above-mentioned dual-shape-core structure or depressed cladding/dual-shape-core structure, whose zero-dispersion wavelength is shifted to the shorter wavelength side or longer wavelength side than the center wavelength of signal light (Japanese Patent Application Laid-Open No. 7-168046 and U.S. Patent No. 5,483,612). Here, the nonlinear optical effects refer to phenomena in which signal light pulses are distorted in proportion to density of light intensity or the like due to nonlinear phenomena such as four-wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), or the like. Transmission speed and relaying intervals in repeating transmission systems are restricted by the nonlinear optical effects.

Japanese Patent Application Laid-Open No. 8-248251 proposes an optical fiber having a configuration which suppresses the occurrence of the above-mentioned nonlinear optical phenomena, which may be generated when light having a high power is incident on the optical fiber, thereby reducing the distortion in optical signals caused by these nonlinear optical phenomena. Such an optical fiber has a refractive index profile whose effective core cross-sectional area A_{eff} is designed to be greater than about 70 μm^2.

Here, as disclosed in Japanese Patent Application Laid-Open No. 8-248251, the effective core cross-sectional area A_{eff} is given by the following expression (1):

$$A_{eff} = 2\pi\left(\int_0^\infty E^2 r dr\right)^2 / \left(\int_0^\infty E^4 r dr\right) \qquad (1)$$

wherein E is an electric field accompanying propadated light, and r is a radial distance from the core center.

On the other hand, dispersion slope is defined by the gradient of a graph indicating a dispersion characteristic in a predetermined wavelength band.

SUMMARY OF THE INVENTION

Having studied the foregoing prior art, the inventors have found the following problems.

In general, while the dispersion slope increases as the effective core cross-sectional area A_{eff} is greater, no consideration has been made in the conventionally proposed dispersion-shifted fibers so as to optimize their dispersion slope value, which relates to the occurrences of distortion in signal light waveform due to dispersion and nonlinear optical effects, from the viewpoint of reducing distortion in the whole waveform.

Accordingly, in view of future advances in wavelength division multiplexing accompanying more sophisticated communications, expected is a situation where it is difficult to keep a transmission quality by simply employing a conventional dispersion-shifted fiber.

In order to overcome the problems such as those mentioned above, it is an object of the present invention to provide a dispersion-shifted fiber for WDM transmission, suitable for long-haul submarine cables or the like, which has a structure for effectively restraining the nonlinear optical phenomena from occurring.

The dispersion-shifted fiber according to the present invention is a single-mode optical fiber for propagating signal light in a 1.55 μm wavelength band (namely, a wavelength in the range of 1,500 nm to 1,600 nm) comprising a core region extending along a predetermined reference axis and a cladding region disposed around the outer periphery of the core region. This dispersion-shifted fiber has a zero-dispersion wavelength shifted to a shorter wavelength side or longer wavelength side from the center wavelength (1,550 nm) of the 1.55-μm wavelength hand.

In particular, as characteristics at the center wavelength (1,550 nm) of the 1.55-μm wavelength band, the dispersion-shifted fiber according to the present invention has, at least, a dispersion whose absolute value is 1.0 to 4.5 ps/nm/km, a dispersion slope of 0.05 to 0.09 ps/nm^2/km, an effective core cross-sectional area of at least 70 μm^2, and a cutoff wavelength of at least 1,300 nm at a fiber length of 2 m.

In general, at a time of wavelength division multiplexing transmission, if the dispersion slope is small, a four-wave mixing which greatly distorts the waveform of a signal light is apt to occur. When the dispersion slope is large, on the other hand, the waveform of signal light is greatly distorted due to the synergistic effect of accumulated dispersion and self-phase modulation.

As a result of studies, the inventors have found that, in the case where, at a wavelength of 1,550 nm, the absolute value of dispersion is 1.0 to 4.5 ps/nm/km and the effective core cross-sectional area is 70 μm^2 or greater, the total amount of distortion in signal light waveform can be reduced in a long-haul transmission if the dispersion slope is 0.05 to 0.09 ps/nm^2/km. Here, the total amount of distortion refers to the sum of the distortion in signal light waveform caused by the four-wave mixings and the distortions in signal light waveform caused by the synergistic effect of accumulated dispersion and self-phase modulation. Thus, the dispersion-shifted fiber according to the present invention can restrain the distortion from occurring due to the nonlinear optical effects, thereby allowing high-quality signal transmission to be realized.

Further, in the dispersion-shifted fiber according to the present invention, the core region is constituted by an inner core having a first refractive index, and an outer core disposed around the outer periphery of the inner core and having a second refractive index higher than the first refractive index; whereas a cladding region having a refractive index lower than the second refractive index is disposed around the outer periphery of the outer core. It means that this dispersion-shifted fiber can be suitably realized by a single-mode optical fiber having a refractive index profile of a ring-shaped core structure.

In a dispersion-shifted fiber having a refractive index profile of a dual-shape-core structure or depressed cladding/dual-shape-core structure, while its effective core cross-sectional area A_{eff} is known to become large, its mode field diameter (MFD) also increases. This can also be seen from the fact that, as disclosed in Japanese Patent Application Laid-Open No. 8-220362, effective core cross-sectional area A_{eff} and MFD satisfy the following expression:

$$A_{eff} = k \cdot \pi \cdot (MFD/2)^2 \qquad (2)$$

wherein k is a correction coefficient. Here, the effective core cross-sectional area A_{eff} is given by the above-mentioned expression (1).

In a dispersion-shifted fiber having a refractive index profile of a ring-shaped core structure, by changing its core diameter (outside diameter of the outer core) while keeping the ratio between the outside diameter of the inner core and the outside diameter of the outer core constant, the inventors have found the following facts. Namely, within a range where the core diameter is small, the greater is the core diameter, the smaller becomes the effective core cross-sectional area A_{eff}. Within a range where the core diameter is considerably large, by contrast, the effective core cross-sectional area A_{eff} increases together with the core diameter. It means that there are two core diameter values yielding the same effective core cross-sectional area A_{eff} in a dispersion-shifted fiber having a refractive index profile of a ring-shaped core structure.

Similarly, in the dispersion-shifted fiber having a refractive index profile of a ring-shaped core structure, when the core diameter (outside diameter of the outer core) is changed while the ratio between the outside diameter of the inner core and the outside diameter of the outer core is kept constant, the dispersion slope changes as well. Namely, within a range where the core diameter is small, in response to increase in core diameter, the dispersion slope as well as the effective core cross-sectional area A_{eff} decreases. Within a range where the core diameter is considerably large, by contrast, while the effective core cross-sectional area A_{eff} increases in response to increase in the core diameter, the dispersion slope decreases. It means that, in the dispersion-shifted fiber having a refractive index profile of a ring-shaped core structure, there is a region of core diameter where the dispersion slope decreases in response to increase in the effective core cross-sectional area A_{eff}.

In view of the foregoing, it is possible to obtain a dispersion-shifted fiber having both of an effective core cross-sectional area A_{eff} which is controlled so as to became greater and a dispersion slope which is controlled so as to become smaller.

Consequently, when setting the effective core cross-sectional area A_{eff} to a predetermined level, a desired dispersion slope value can be appropriately selected from two different dispersion slope values, thus making it easy to realize the dispersion-shifted fiber according to the present invention.

Further, in the dispersion-shifted fiber having a

refractive index profile of a ring-shaped core structure, within a range where the core diameter is small, both effective core Cross-sectional area A_{eff} and MFD decrease as the core diameter increases. Within a range where the core diameter is considerably large, as the core diameter increases, the MFD decreases, whereas the effective core cross-sectional area A_{eff} increases. Here, when changing the core diameter (outside diameter of the outer core), the ratio between the outside diameter of the inner core and the outside diameter of the outer core is kept constant. In general, bending loss becomes smaller as the MFD is smaller and the cutoff wavelength is longer. From this viewpoint, the larger the diameter of the core is, the more advantageous it becomes.

Specifically, according to the findings of the inventors, in order to realize a dispersion-shifted fiber having the above-mentioned characteristics, it is necessary to satisfy the following relationships:

$$0.4 \leq Ra\ (= 2a/2b) \leq 0.8$$

$$5\ \mu m \leq 2b \leq 14\ \mu m$$

wherein 2a is an outside diameter of the inner core, and 2b is an outside diameter of the outer core.

Also, this dispersion-shifted fiber satisfies the following relationship:

$$\Delta n_1 - \Delta n_2 \geq 1\%$$

wherein Δn_1 is a relative refractive index difference or the outer core with respect to the cladding region, and Δn_2 is a relative refractive index difference of the inner core with respect to the cladding region. Namely, since the dispersion value of the dispersion-shifted fiber depends on an amount of depression (Δn_1 - Δn_2) of a depressed area corresponding to the core center region in its refractive index profile in the diameter direction within the core region, it is necessary for this amount of depression to be at least 1.0% in order to obtain a sufficient dispersion value. The above-mentioned relationship between the outside diameter 2a of the inner core and the outside diameter 2b of the outer core is independent of the values of relative refractive index differences Δn_1 and Δn_2.

Further, reducing the relative refractive index difference Δn_2 of the inner core with respect to the cladding region (enhancing its absolute value when it is negative) is effective in shortening cutoff wavelength. Accordingly, taking account of short-haul light transmission, in order to yield a cutoff wavelength of 1,550 nm or less at a fiber length of 2 m, it is necessary for Δn_2 to be not greater than -0.4%.

Though the cladding region can have a unitary structure (hereinafter referred to as matched cladding structure), it can also be constituted by an inner cladding disposed around the outer periphery of the outer core and having a third refractive index lower than the second refractive index (refractive index of the outer core), and an outer cladding disposed around the outer periphery of the inner cladding and having a fourth refractive index higher than the third refractive index. Namely, the dispersion-shifted fiber can have a refractive index profile of a depressed cladding/ring-shaped core structure (double structure).

Since the dispersion-shifted fiber having a depressed cladding structure has an effect to decrease undesired 2-mode light, as compared with the dispersion-shifted fiber having a matched cladding structure without a depression, the depressed cladding Structure is effective to make a cutoff wavelength of 2-mode light become short. However, in the refractive index profile of the depressed cladding structure, when a width, which corresponds to a thickness (c-b) of the inner cladding, of a depression to be provided therein becomes too narrow (namely, the value 2c/2b approaches 1) or when a width of a depression provided therein becomes too wide (namely, the value 2c/2b becomes too large), an effect of the depressed cladding structure with respect to the matched cladding structure can not be obtained. Therefore, it is necessary that the inner cladding has an appropriate outer diameter to the outer core, and it is preferable that the dispersion-shifted fiber having a refractive index profile of a depressed cladding/ring-shaped core structure satisfies the following relationship:

$$1.2 \leq 2c/2b \leq 2.2.$$

In the dispersion-shifted fiber having a refractive index profile of a depressed cladding/ring-shaped core structure, Δn_1 is a relative refractive index difference of the outer core with respect to the outer cladding, whereas Δn_2 is a relative refractive index difference of the inner core with respect to the outer cladding. In this case, its cutoff wavelength becomes shorter than that of a dispersion-shifted fiber having a refractive index profile of a simple ring-shaped core structure with no depressed cladding structure, even when the values of relative refractive index differences Δn_1 and Δn_2 in the former are the same as those in the latter.

On the other hand, in the conventional optical fiber disclosed in the above-mentioned Japanese Patent Application Laid-Open No. 8-248251, the optical power distribution (or electromagnetic field distribution) is maximized at the core center of the optical fiber. In order to increase the effective core cross-sectional area A_{eff} while maintaining the form of optical power distribution having such a characteristic, it is necessary to broaden a skirt portion in the optical power distribution. Thus, in order to broaden the skirt portion in the optical power distribution, the conventional optical fiber is provided with another segment (outer core) disposed outside the center segment (inner core).

As can also be seen from the above-mentioned

expression (2), however, in the above-mentioned dispersion-shifted fiber having a refractive index profile of a dual-shape-core structure or depressed cladding/dual-shape-core structure, when the effective core cross-sectional area A_{eff} is increased, mode field diameter (MFD) increases together therewith.

Due to the foregoing reasons, the optical fiber of the above-mentioned Japanese Patent Publication Laid-Open No. 8-248251, which is designed so as to enlarge the effective core cross-sectional area A_{eff}, may be problematic in that bending loss increases as the effective core cross-sectional area A_{eff} becomes larger.

Therefore, in order to effectively restrain the nonlinear optical phenomena from occurring while keeping the value of MFD small, the dispersion-shifted fiber according to the present invention has, at least, a refractive index profile of a ring-shaped core structure, thereby, in a cross section perpendicular to a wave-guiding direction of signal light, the part where the optical power distribution in the fundamental mode of signal light or its accompanying electromagnetic field distribution is maximized is radially separated from the center of the core region by a predetermined distance.

Even in an optical fiber having a refractive index profile of a ring-shaped core structure, when the outside diameter of its inner core is small, it does not yield a large difference in terms of the optical power distribution of propagated light or its accompanying electromagnetic field distribution as compared with an optical fiber having a refractive index profile other than that of the ring-shaped core structure. Namely, even in the optical fiber having a refractive index profile of a ring-shaped core structure, when the outside diameter of the inner core is small, the part where the optical power distribution of signal light in the fundamental mode or electromagnetic field distribution is maximized becomes to substantially overlap with the center of the core region. In such a state, the characteristic of the refractive index profile with a ring-shaped core structure can not fully be exhibited.

Specifically, in the dispersion-shifted fiber according to the present invention, in a cross section perpendicular to a wave-guiding direction of signal light, the part where the optical power distribution of signal light in a fundamental mode or its accompanying electromagnetic field distribution is maximized is radially separated from the center of the core region by about 0.5 µm to about 5 µm.

In this case, satisfying the condition of expression (3) mentioned in the following is particularly preferable in order to fully exhibit the effects of the refractive index profile with a ring-shaped core structure. Namely, the dispersion-shifted fiber according to the present invention satisfies a relationship of:

$$P_1 > 1.2 \times P_0 \qquad (3)$$

wherein P_0 is an optical power of signal light in the fundamental mode at the center of the core region or an intensity of its accompanying electromagnetic field, and P_1 is a maximum value, in a radial direction from the center of the core region, of optical power distribution of signal light in the fundamental mode or its accompanying electromagnetic field distribution.

As a result, while keeping the MFD of the dispersion-shifted fiber at a small value, the effective core cross-sectional area A_{eff} can be made greater, thereby the nonlinear optical phenomena can be reduced without increasing bending loss.

The dispersion-shifted fiber according to the present invention is a dispersion-shifted fiber whose zero-dispersion wavelength is shifted from the center wavelength (1,550 nm) of the above-mentioned 1.55-µm wavelength band by a predetermined amount. Thus, as the effective core cross-sectional area A_{eff} is enlarged while the zero-dispersion wavelength is shifted, signals can be more effectively restrained from deteriorating due to four-wave mixing.

The present invention will be more fully understood from the detailed description given hereinbelow and the accompanying drawings, which are given by way of illustration only and are not to be considered as limiting the present invention.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter- However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will be apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a view showing a cross-sectional structure of a dispersion-shifted fiber according to a first embodiment of the present invention and its refractive index profile in a diameter direction;

Fig. 2 is a graph showing, in a dispersion-shifted fiber having a refractive index profile of a ring-shaped core structure, changes in effective core cross-sectional area A_{eff} and MFD when its core diameter 2b (outside diameter of the outer core) is changed;

Fig. 3 is a graph showing, in a dispersion-shifted fiber having a refractive index profile of a ring-shaped core structure, changes in cutoff wavelength λ_c and dispersion slope at a fiber length of 2 m when its core diameter 2b (outside diameter of the outer core) is changed;

Figs. 4 to 7 are graphs for explaining changes in bit error rate (BER) caused by changes in dispersion slope, respectively showing those at dispersion slopes of 0.03 ps/nm^2/km, 0.05 ps/nm^2/km, 0.09 ps/nm^2/km, and 0.12 ps/nm^2/km;

Fig. 8 is a view for explaining Q value;

Fig. 9 is a view for explaining an optical power distribution in the fundamental mode of signal light in the dispersion-shifted fiber of Fig. 1 (including its cross-sectional structure and its refractive index profile in a diameter direction);

Fig. 10 is a view for explaining an optical power distribution in the fundamental mode of signal light in a dispersion-shifted fiber according to a comparative example of the first embodiment (including its cross-sectional structure and its refractive index profile in a diameter direction);

Figs. 11 and 12 are views each showing a cross-sectional structure of a dispersion-shifted fiber according to a modified example of the first embodiment and its refractive index profile in a diameter direction;

Fig. 13 is a view showing a cross-sectional structure of a dispersion-shifted fiber according to a second embodiment of the present invention and its refractive index profile in a diameter direction;

Fig. 14 is a view for explaining an optical power distribution in the fundamental mode of the signal light in the dispersion-shifted fiber of Fig. 13 (including its cross-sectional structure and its refractive index profile in a diameter direction);

Figs. 15 and 16 are views each showing a cross-sectional structure of a dispersion-shifted fiber according to a modified example of the second embodiment and its refractive index profile in a diameter direction;

Fig. 17 is a table for explaining tolerances of structural parameters for realizing various characteristics of the dispersion-shifted fiber according to the present invention;

Fig. 18 is a graph showing a relationship between the outside diameter of the inner core and the outside diameter of the outer core for realizing various characteristics of the dispersion-shifted fiber according to the present invention;

Fig. 19 is a graph showing an electromagnetic field distribution (corresponding to an optical power distribution) in a diameter direction in the dispersion-shifted fiber according to the present invention;

Fig. 20 is a graph showing a relationship between distance (μm) from the center of the core region to a position where the electromagnetic field value (corresponding to optical power) is maximised and MFD (μm) in the dispersion-shifted fiber according to the present invention;

Fig. 21 is a graph showing a relationship between distance (μm) from the center of the core region to a position where the electromagnetic field value (corresponding to optical power) is maximized and increase in loss (dB/km) caused by microbend;

Fig. 22 is a table showing various characteristics of specific samples in the dispersion-shifted fiber according to the present invention;

Fig. 23 is a graph showing an example of refractive index profile in the dispersion-shifted fiber according to the present invention and its optical power distribution along a diameter direction thereof; and

Figs. 24 to 27 are views showing examples of refractive index profile applicable to the dispersion-shifted fiber according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the following, embodiments of the dispersion-shifted fiber according to the present invention will be explained with reference to Figs. 1 to 27. In the explanation of the drawings, constituents identical to each other will be referred to with numerals identical to each other without their overlapping descriptions being repeated.

Embodiment 1

Fig. 1 is a view showing a cross-sectional structure of a dispersion-shifted fiber according to a first embodiment of the present invention and its refractive index profile in a diameter direction. AS shown in Fig. 1, this dispersion-shifted fiber 100 is a single-mode optical fiber mainly composed of silica glass for propagating signal light in a wavelength band of 1.55 μm (1,500 to 1,600 nm), comprising an inner core 111 having an outside diameter of 2a and a refractive index of n_1; an outer core 112 disposed around the outer periphery of the inner core 111 and having an outside diameter of 2b (i.e., diameter of a core region 110 is 2b) and a refractive index of n_2 ($> n_1$); and a cladding region 210 disposed around the outer periphery of the outer core 112, having a refractive index of n_3 ($< n_2$). Here, the core region 110 is constituted by the inner core 111 and the outer core 112. Also, a refractive index profile 101 indicates refractive index at each part on line L1 in the drawing.

The dispersion-shifted fiber 100 is set such that, as characteristics at a wavelength of 1,550 nm, its absolute value of dispersion is within the range of 1.0 to 4.5 ps/nm/km, dispersion slope is within the range of 0.05 to 0.09 ps/nm^2/km, effective core cross-sectional area is at least 70 μm^2, and cutoff wavelength at 2 m length is at least 1,300 nm.

In a preferred example thereof, when the refractive index n_1 equals to the refractive index n_3 (i.e., relative refractive index difference Δn_2 of the inner core 111 with respect to the cladding region 210 is zero), the relative refractive index difference Δn_1 of the outer core 112 with respect to the cladding region 210 which is defined by:

$$\Delta n_1 = (n_2{}^2 - n_3{}^2)/(2n_3{}^2) \quad (4)$$

is 1.5%, the core diameter (outside diameter 2b of the outer core 112) is 9 μm, and ratio Ra (= a/b) of the outside diameter 2a of the inner core 111 to the diameter